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PROJECT MICHAEL

CONTRACT N6-ONR-27135

Technical Report No. 15

Transmission of 30 cps
Sound in Deep Water

by

H. L. Poss

COLUMBIA UNIVERSITY

HUDSON LABORATORIES

DOBBS FERRY, N. Y.

RESEARCH SPONSORED BY

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Director

Research Sponsored by
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TRANSMISSION OF 30 CPS SOUND IN DEEP WATER

by

H. L. Poss

ABSTRACT

The transmission of 30 cps sound in deep water has been studied using bottomed detectors at Bermuda and Puerto Rico. An A Mark 6(b) minesweeping gear, modified to operate synchronously at 30 cps, was used for a sound source.

The radiation pattern of the source at short range is in agreement with that calculated from a source plus image model. At increased range, the experimental values fall off less rapidly than the model predicts because of bottom reflections and transmission in the bottom layers. At large ranges, in work southeast of Bermuda, sound pressure falls off at an inverse square rate out to about 10 miles after which it approaches cylindrical spreading. At Puerto Rico, north of San Juan, sound pressure is proportional to $R^{-3/2}$ out to 30 miles. Spot measurements were continued out to 300 miles and are consistent with the peaks and dips appearing in more detailed shot data and a ray analysis available for this area. The initially rapid fall off is determined by bottom constants and slope parameters.

A study of possible broadening of the signal in its transmission through the ocean was made both by passing it through a bank of very sharp filters and by a phase comparison method which enabled the small Doppler shift in frequency to be determined. Although at times subject to large amplitude fluctuations which obscured the phase measurements, at other times, the signal maintained its phase coherency out to the full distance of 300 miles.

INTRODUCTION

One of the problems that has been investigated at Hudson Laboratories in the field of sound propagation concerns the transmission of a 30 cps signal in deep water. In addition to measuring sound pressure as a function of source to detector distance, we also wished to determine if such a signal becomes broadened in its passage through the ocean so that when received its energy would be distributed over a frequency band appreciably wider than the initial one. Such information would be of value in planning long range listening systems based on arrays or sharp filters. It would also be of use in considering methods for long range underwater communication between submerged submarines and in studying the feasibility of low frequency sonar systems.

The first problem was to develop a source which would be stable in frequency to about one part in 10,000 at 30 cps since we hoped to distinguish frequency changes of this order. For this purpose, it proved possible to modify an A Mark 6(b) minesweeping gear. This type of sound source contains a 7 1/2 hp dc motor which drives two opposed pistons through an eccentric mechanism. The piston diameters are 27 inches and their amplitudes of motion are each 1/8 inch. From these dimensions, the calculated acoustic power output at 30 cps is 200 watts. The modification consisted of placing a 1 hp 1800 rpm synchronous motor on the same shaft as the dc motor. The synchronous motor is fed from a 1 kw vacuum tube power amplifier driven by a tuning fork controlled oscillator. The dc motor itself is fairly stable and supplies most of the power. The synchronous motor is thus not required to exceed its rating and in practice maintains the shaft at synchronous speed over long periods of operation. Details of the modification may be found in another report.[1]

The source was towed by the USS ALLEGHENY for the measurements reported herein. Operations were conducted off the eastern end of Bermuda, using the Navy Sofar Station geophone to detect the signal, and north of San Juan, Puerto Rico, where this laboratory has its own hydrophone installation. At Bermuda, the source was towed out to a distance of 140 miles. At Puerto Rico, the radiation pattern of the source was studied when it was in the vicinity of the hydrophones. In addition, it was operated out to a distance of 300 miles. The source depths used in the measurements were 42 ft and 84 ft, these being one-quarter and one-half wavelength, respectively, for 30 cps sound. The hydrophones used as detectors were Bell Laboratories' moving coil units type GS-55156.

Preliminary accounts of some of these measurements have been given in previous reports.[2,3,4]

INSTRUMENTATION

A. Sound Level

A block diagram of the equipment used at Puerto Rico is shown in Fig. 1. The moving coil hydrophone is transformer coupled to a preamplifier at the cable termination on the beach. The preamplifier output, at a low impedance level, is sent by underground cable a distance of several hundred feet to the laboratory. The signal then goes through a 30 cps amplifier having a bandwidth of 1 cps between the half power points. The amplifier is patterned after a commercial design and employs a twin-T network in a frequency-selective feedback loop. To record sound pressure level, the amplifier output was connected to a Brüel & Kjaer logarithmic level recorder having a 50 db range.

There are two moving coil hydrophones at Puerto Rico, one at a depth of 200 fathoms and the other at a depth of 470 fathoms. The calibration circuit indicated in the block diagram enabled a known 30 cps signal to be introduced in series with one of the moving coil hydrophone leads so that the gain of the overall system could be measured. The hydrophones had been calibrated before being installed so that it was possible to convert the hydrophone output voltage into dynes/cm^2 to obtain the sound pressure.

B. Line Width and Doppler Shift

To measure broadening of the signal, one method of approach was to pass the signal through a bank of very sharp filters in order to examine it for possible structure. Another means was to measure, by a phase comparison method, the small Doppler shift caused by the motion of the sound source through the water. It was possible to measure such shifts fairly well indicating that the line width was small compared to the shift.

The sharp filters were also used to detect the signal and to measure sound pressure in regions where the signal-to-noise ratio was too low to permit reliable measurements to be made with the 30 cps amplifier alone.

The filters represent a somewhat unconventional use of commercially available components. It has been found that tuning forks of the type intended for oscillator applications* can be used as

* Tuning forks were supplied by the Riverbank Laboratories, Geneva, Illinois.

very sharp filter elements. Opposite each tine of the fork is a coil wound on a magnetic core. If an alternating voltage of the fork's resonant frequency is applied to one coil, the fork is set into vibration and an alternating voltage of the applied frequency is induced in the second coil. If the applied frequency is not the resonant frequency, the fork vibrates only weakly because it constitutes a high Q mechanical system, and the output voltage is much lower than at resonance.

The tuning fork and the associated coils thus constitute a very selective filter, the critical properties of which, such as resonant frequency, bandwidth, and stability, are determined by the fork. Tuning forks are presently available which have very low damping and a frequency stability of a part per million per degree centigrade.

The response of typical tuning fork filters that we have used at 30 cps is illustrated in Figs. 2a and 2b. The response curve in Fig. 2b was determined directly by varying the input frequency in small steps in the vicinity of resonance. The tuning forks have adjustable screw type weights which permit their frequencies to be varied over a range of about 0.1 cps. An oscillator controlled by one such tuning fork was used in the measurement. The frequency increments were measured by comparing its frequency with that of a fixed tuning fork oscillator. In Fig. 2b, the selectivity was inferred from a measurement of the decay of the oscillations when the input to the filter was removed. The exponential character of the decay is evidence that the filter obeys the equations for a damped linear oscillator or analogous R-L-C circuit, the oscillations of which, for the case of low damping, decay as $e^{-\pi \Delta f t}$ or $e^{-\pi f t/Q}$.

Here, f is the resonant frequency, Δf is the bandwidth between the half power points, and Q is defined as $f/\Delta f$.

A bank of eight filters was used tuned at 0.01 cps intervals above and below 30 cps. They have Q's of 8000, their bandwidths then being less than 0.004 cps. The input and output coils of the tuning forks have resistances of 1600 ohms. The eight input coils are in parallel and were driven by a separate amplifier to prevent loading down the 30 cps amplifier. Input voltages were kept below 0.3 volts, for if the forks are caused to vibrate at too great an amplitude, their frequencies shift slightly and their outputs are no longer linear with respect to the applied voltage. The outputs of the filters are several hundredths of a volt and may be read directly with a sensitive vacuum tube voltmeter. For continuous records, the outputs were amplified by Tektronix type 122 preamplifiers, rectified, and then fed to linear level recorders.

The transient response of three filters to the sudden application of a 30 cps test signal is shown in Fig. 3. The traces are recordings of the filter output voltage amplitudes. The outputs of the off-frequency filters first fluctuate because of beats between the filters' natural frequencies and the applied frequency. Several minutes are required before the steady state condition is established because of the low damping. The steady state value is seen to be largest for the filter tuned to the applied frequency.

The Doppler shifted frequency of the source could be obtained directly by noting which particular tuning fork filter had the highest output, but this effect was more conveniently studied by a phase comparison method.

The Doppler shift in frequency is

$$\Delta f = \pm f\ (v/c)$$

for source velocities v small compared with the sound velocity c.

The shift for f equal to 30 cps is then

$$\Delta f = \pm 0.010v$$

the source velocity v being measured in knots. For typical towing speeds of 2 to 3 knots, Δf is accordingly 0.02 to 0.03 cps.

To measure Δf by the phase comparison method, the signal, filtered through the 30 cps amplifier, is connected to one channel of a phasemeter.* A 30 cps tuning fork oscillator is connected to the other channel as indicated in the block diagram (Fig. 1). The frequency of this oscillator had been previously set to be one-half the frequency of the 60 cps tuning fork oscillator which operates the synchronous motor of the sound source through a power amplifier as described in the Introduction. The output of the phasemeter indicates the phase difference between the signals in each channel and was recorded on a recording dc milliammeter.

Thus, if the reference voltage applied by the tuning fork oscillator, $V_1 \sin 2\pi ft$, is connected to channel A and the signal, $V_2 \sin 2\pi (f + \Delta f) t$ is connected to channel B, the phase difference between channels A and B is

$$\phi_A - \phi_B = -2\pi\Delta ft.$$

If in a time T, $\phi_A - \phi_B$ changes by 2π,

$$\Delta f = \pm 1/T.$$

* Technology Instrument Corporation, Model 320-A.

The time T is measured directly from the phasemeter trace, examples of which are discussed in the following section. Δf is positive if $\phi_A - \phi_B$ is observed to decrease in time, and negative if the opposite is true.

MEASUREMENTS

A. Short Ranges

The radiation pattern of the sound source may be simply calculated on a source plus image basis where the image is a distance above the surface equal to the source depth and is equal but opposite in phase to the source. The boundary condition of zero pressure is then satisfied for the free surface of the ocean. Because of bottom reflections and deviations of the ray paths from straight lines, the observed results cannot be expected to agree with the theoretical ones for large source to detector distances. Nevertheless, the calculations provide a basis for a more detailed analysis.

The source can be treated as spherical since its dimensions are small compared to wavelength. Referring to the diagram in Fig. 4, we take the source and image pressures to be

$$(C/R_2)e^{jkR_2} \quad \text{and} \quad -(C/R_1)e^{jkR_1}$$

respectively, where the time factor has been suppressed. For distances large compared with the source depth d, the resultant pressure amplitude is then

$$P = (2C/R) \sin (kd \sin \theta)$$

R is the distance from the observation point to the center of the source - image axis, $k = 2\pi/\lambda$, and θ is the angle between the surface and R. Fig. 4 shows the polar plots of pressure amplitude for source depths of one-quarter and one-half wavelength. For the half-wavelength depth, there is a null below the source, the maximum radiation occurring for $\theta = 30°$, while for the quarter-wavelength depth, the maximum radiation is directly downward. For small values of θ, the pressure amplitude for the half-wavelength depth is twice that for the quarter-wavelength depth.

A series of runs were made in which the source was towed over both hydrophones so that the observed radiation pattern at close range could be compared with that expected from the source plus image calculation. Runs were made in the east-west direction

(parallel to shore) and in the north-south direction. The USS ALLEGHENY, which was towing the source, was tracked by two shore based transit stations. The stations radioed their readings to the ship so that it could follow a preassigned course. The transit readings were sufficiently accurate to locate the ALLEGHENY to within about 50 yards at any time during the run.

The location of the hydrophones had been determined previously by measuring the first arrival times of sound from shots fired by the ALLEGHENY in a series of tracks near the hydrophones. The intersection of the perpendicular to a track at the point of minimum travel time with like perpendiculars to other tracks determines the hydrophone position. As a check, it was also possible to determine the hydrophone location during a run with the sound source by similarly drawing perpendiculars to the tracks at the points where the Doppler shift was zero.

An example of such a determination for the case of the shallow hydrophone is shown in Fig. 5. The trace is a record of the phase difference between a reference oscillator and the signal as described under Instrumentation. The retrace lines occur where the meter jumps between the equivalent 0° and 360° positions. The phase difference is first observed to be decreasing with time showing that the signal frequency is higher than the standard, indicating approach. As time increases, the rate of change of phase decreases until it is momentarily zero at the point of closest approach. It then starts to increase, meaning a lowered signal frequency and indicating recession from the hydrophone. Since the ALLEGHENY'S speed was only about 100 yd/min, the zero point can be located quite well.

A continuous record of sound pressure level was made on the logarithmic level recorder. For ranges over 1000 yd, in the case of the shallow hydrophone, and over 2000 yd, for the deep hydrophone, a number of sharp minima occurred in the sound level record. It appears plausible to identify these with interference minima resulting from sound reaching the hydrophone over more than one path. For example, some dips can be attributed reasonably well to interference between the direct ray and the one critically refracted in the bottom layer. Irregularities in the bottom contours and uncertainty in the bottom constants prevent the identification from being certain.

Sound levels were converted to decibels above one dyne/cm^2 using the calibration system mentioned under Instrumentation. The absolute calibration of the hydrophones is described in another report.[5] The mounted hydrophones were calibrated in water at the U.S. Navy Underwater Sound Reference Laboratory in Orlando, Florida, down to 40 cps so that it was necessary to extrapolate the curves to 30 cps. Unfortunately, there is an uncertainty of several decibels in the extrapolation because of other measurements on the hydrophones made at the

Bell Telephone Laboratories which conflict with those from Orlando. The uncertainty is in a direction to lower sound pressure values based on the Orlando measurements.

Neglecting the series of minima mentioned above, in Figs. 6a and 6b pressure levels are plotted against range for runs over the deep and shallow hydrophones at the two source depths. Curves based on the source plus image model are included for comparison. They have been normalized to the experimental curves at the maximum values of the latter.

It can be seen that the experimental curves match the theoretical ones fairly well in the vicinity of the hydrophones but that for increasing range, the experimental values fall off less rapidly. The discrepancy is an indication of the amount of sound energy reaching the hydrophones because of bottom reflections and transmission in the bottom layers. Conditions were not sufficiently ideal for the null to be complete at the half-wavelength depth.

The absolute values of sound pressure at the hydrophones may be readily calculated from the source plus image model. For spherical radiation from a simple source, the pressure amplitude is

$$P = \frac{\rho c k}{4 \pi R} Q$$

The source strength Q for a uniformly vibrating body equals the product of surface area and velocity amplitude. For the sound source

$$Q = \pi^2 D^2 f A$$

where D is the piston diameter, f is the frequency, and A is the piston amplitude.

When the source at the quarter-wavelength depth is over a hydrophone, the source and image pressures add so that

$$P = \pi^2 \rho D^2 f^2 A/R$$

The ratio of sound pressures for the source over the shallow and over the deep hydrophone should then be inversely as the ratio of their depths. Their depths being 200 and 470 fathoms, the pressure levels with the source over each should differ by 7.3 db. It should be noted that the ratio is unchanged if the sound pressure at the hydrophone is assumed to result from the incident sound plus a certain fraction of reflected sound as long as the fraction is the same at both hydrophones.

Taking $\rho = 1.023$ gm/cm^3 as an average for sea water and inserting the source constants mentioned in Introduction, the calculated rms pressures, referred to one dyne/cm^2, for the source at a quarter wavelength depth over the hydrophones are

shallow: P = 48.4 db

deep: P = 41.1 db

The average of the experimental values of these quantities measured in the different runs is

shallow: P = 55.8 db

deep: P = 48.3 db

The observed difference between the shallow and deep hydrophones of 7.5 db agrees well with the calculated 7.3 db, the uncertainties in the measurements being greater than the difference of 0.2 db. The absolute values, however, are seen to be 7 db higher than the calculated ones. Part of the discrepancy may be attributable to bottom reflected sound which the calculation neglects. Another part might result from a possible error in the hydrophone calibration previously discussed. Both of these effects are in the direction to bring the calculated and observed values into agreement. However, in the absence of definite information on these effects, the hydrophone calibration originally assumed has been adhered to in all of the measurements.

B. Long Ranges

Measurements with the source at large distances from the detector have been carried out off Bermuda and Puerto Rico as summarized in Introduction. The maps in Figs. 7A and 7B show the areas in which operations were conducted.

The Bermuda operations were carried out in October, 1952, using the Navy Sofar Station geophone located at a depth of 425 fathoms off the eastern end of Bermuda. The source at a depth of 42 ft was towed by the USS ALLEGHENY at a speed of 3 knots on a course southeast from the geophone out to a range of 140 miles. The water depth averaged about 2400 fathoms beyond 25 miles. The detection equipment was similar to that shown in Fig. 1. The calibration of the geophone was not known so that absolute sound levels could not be obtained.

The source was operated about one hour out of every three during the run. Records were obtained on the logarithmic level recorder and on the phasemeter. A part of the level recorder trace made when the source was 120 miles from the geophone is shown in Fig. 8. The source was towed about three miles in the interval covered by the trace. The background noise coming through the 30 cps amplifier just before the arrival of the source signal may be seen at the extreme left. The signal has large fluctuations and occasionally drops down to the background level. At other times, the level remains fairly constant, as in the vicinity of the time mark at 2037 where it is about 20 db above background. The phasemeter trace at such times (Fig. 9) shows the signal to be well defined in frequency, permitting an accurate measurement to be made of the Doppler shift. The trace in Fig. 9 shows the source to be approaching the geophone at a speed of 3.9 knots.

Other evidence for the sharpness of the signal in the absence of fluctuations was obtained from the tuning fork filters. There were no provisions for recording the filter outputs during the Bermuda operations but the outputs of several could be read with vacuum tube voltmeters. The filter tuned closest to the shifted frequency had an output greater than the neighboring filters by an amount comparable to that obtained when the filter bank is fed with a fixed frequency test signal.

The average speed of the ALLEGHENY over the outgoing and return runs as calculated from the Doppler measurements agreed with the average speed determined by taking Loran fixes at intervals during the run to 0.1 knot. The agreement shows that only rays leaving the source at shallow angles reach the geophone, for otherwise the speeds calculated from the Doppler effect would be too low.

The geophone output vs range is plotted in Fig. 10. The signal levels plotted are average values away from the vicinity of the large fluctuations. The leveling off of the signal for the closest points is not understood but may have been a result of local bottom conditions. Out to 10 miles, the pressure falls off at an inverse square rate. There is a transition region between 10 and 20 miles after which the pressure falls off more slowly. The line drawn through the remaining points corresponds to cylindrical spreading, proportional to $R^{-1/2}$. The large scatter prevents an experimental determination of the slope from being made with much accuracy.

Range runs off Puerto Rico were made during February, 1953, using as a detector the deep moving coil hydrophone. In the direction due north from the hydrophone, the first 27 miles in range

were covered almost continuously in a series of runs during which the source was towed at a depth of 42 feet. The towing speed was limited to three knots so that it was not practical to cover the full range by this procedure. Instead, the source was operated at various stations along the range while the ALLEGHENY was drifting. It would then be lifted clear of the water so that normal cruising speed could be maintained to the next station. At each drift station the source was operated at depths of 42 feet and 84 feet. Measurements were made in this manner out to 300 miles. The separation of the drift stations leaves many gaps in the data, but in these exploratory measurements, greater value was attached to obtaining some data at large ranges rather than complete data over a limited range.

In the direction northwest from the hydrophone, a continuous run was made at the 42 foot depth extending in range from 12 to 26 miles. The source was also operated in this direction from the hydrophone at ranges of 50 and 74 miles.

Loran or celestial navigation was used to determine the ship's position at drift stations. As a check, it was possible to determine the ship's distance from the hydrophone in most instances by having the sound source turned off at a specified time, which was communicated to the shore-based laboratory by radio, and noting the interval which elapsed until the hydrophone signal disappeared. When the signal strength was not fluctuating and well above background, this interval could be measured to about one second. In these cases, distances calculated from the times agreed to within several miles with those obtained by navigation methods. In converting times to distances, an average velocity was used and no attempt was made to correct for the fact that the ray paths are greater than the horizontal range.

During the continuous runs, the ship's speed with respect to the hydrophone was known from the phasemeter measurements. Since the course was either toward or away from the hydrophone, this calculated speed was taken to be the actual one and the ship's track as a function of time was determined by fitting a line with a slope corresponding to the average speed through whatever fixes the ship had made in the course of the run.

In the runs to the north beyond 30 miles, the signal-to-noise ratio through the 30 cps amplifier was often too low for reliable measurements to be taken using just the level recorder and recourse was made to the tuning fork filters. In the runs to the northwest and also at Bermuda, the signal was sufficiently above background so that readings could be taken directly from the level recorder. A slight shift in the center frequency of the 30 cps amplifier, probably caused by the effects of humidity on the RC components of the

selective network, was noted to have occurred during part of the run to the north. It would not have affected absolute levels since the overall system was calibrated with a standard 30 cps signal, but would have lowered the signal-to-noise ratio. This effect alone, however, does not seem sufficient to account for the signal being down to background at times and the following factors are likely to be pertinent. The transmission characteristics in the Puerto Rico area, as will be mentioned later, feature zones of very low intensity. Such zones were encountered in the more extensive work to be north but not at the two drift stations made in the northwest direction. Also, the background noise at Puerto Rico was occasionally high because of ship traffic.

In order to measure sound pressure with the tuning fork filters, it was necessary to multiply the filter output by a factor to take into account the attenuation caused by the signal frequency differing slightly from the resonant frequency of the filter. The signal frequency was known with respect to the 30 cps tuning fork oscillator reference standard from the phasemeter record. Even when the output of the 30 cps amplifier was down to background on the level recorder, the frequency difference could still be read moderately well from the phasemeter trace since the uniform rate of change of phase of the signal stands out against the superimposed random phase variations of the background noise. Knowing the Q's of the filters and their resonant frequencies with respect to the standard, the filter corrections could then be made. In the measurements, use was made only of the filters having the highest outputs, that is, those closest to the signal frequency.

The signal level would frequently have large fluctuations at any particular station similar to those observed during the Bermuda run. They appear to be functions of position rather than time since regions of good and poor signal reception were more spread out in time when the ship was drifting than when it was under way. The fluctuations are perhaps attributable to multipath interference effects.

Because of the indirect procedure which is necessary in obtaining sound pressure levels from the tuning fork filters, such values are likely to be more uncertain than those taken directly from the level recorder which are average values away from the vicinity of large fluctuations. In using the tuning fork filters, a value for a particular source depth at a drift station was obtained by taking the time average of the signal, excluding intervals of several minutes in which the transient behavior of the filters predominate, such as occur following the initial arrival of the signal or after a large fluctuation. Unless the signal is constant, differences between the level recorder and tuning fork filter values might be expected because of their differing response times. In

regions where values from both can be compared, an extreme discrepancy of 4 db was noted, the average being about 2 db.

In Fig. 11, sound pressure vs range is plotted for the directions north and northwest from the deep hydrophone. Considering first the northerly direction, the range values extend out to 300 miles. Shot data and a ray analysis covering most of this region have been presented in a previous report.[4] In the region from 3 to 30 miles, sound pressure is proportional to $R^{-3/2}$. The shot data indicate a slower decrease, proportional to $R^{-1.1}$, which the ray analysis can yield using reasonable values for the bottom parameters. The rays from the source which are effective in reaching the hydrophone are those which leave at increasingly smaller angles with the surface as range increases. The faster decrease observed with the sound source could arise from the fact that the radiation from the source decreases with angle.

Beyond 35 miles, the water depth remains greater than 2800 fathoms and deep water transmission is predicted with peaks in intensity at 35 mile intervals and regions of low level in between. The water depth along the course of the Bermuda run was not sufficiently great for this characteristic peaking to be manifest.

The experimental points beyond 27 miles are all based on tuning fork filter values for consistency. They are too widely separated to permit the shape of the curve to be inferred, but are consistent with the peaks and dips appearing in the more detailed shot results. In particular, the point at 38 miles is one of very low level in agreement with the shot data and ray analysis.

In the direction northwest from the hydrophone, the continuous range covered was not extensive enough to enable an average slope to be determined well, considering the spread of the points. No ray tracing has been carried out in this direction. From 12 to 18 miles, the sound pressure decreases on the average. It then increases out to 21 miles after which it falls off rapidly, similar to the sharp drop which occurred in the northerly direction at a somewhat greater range. The remaining points at 50 and 74 miles are almost as high in level as the point at 26 miles.

Values obtained at the 84 foot source depth are also plotted in Fig. 11. On the basis of the radiation patterns, the 84 foot depth should give a pressure level 6 db greater than the 42 foot depth for rays leaving at small angles with the surface. The observed differences range from 3 to 12 db. As has been mentioned, regions of good and poor signal reception which are observed to occur in the same general area seem to be functions of position. Because of the ship's drift, measurements at the two depths at the same station can differ in position by one-half mile and so may not be strictly comparable.

Measurements of the Doppler shift during these range runs again provide evidence for the sharpness of the signal, as was the case during the Bermuda run. Fig. 12 shows the phasemeter record at a time of good signal reception when the source was 50 miles northwest of the hydrophone. The frequency of the standard 30 cps oscillator exceeds the signal frequency by 0.005 cps, as determined from the trace, indicating that the ALLEGHENY was drifting away from the hydrophone at 1/2 knot. The point to be noted in connection with this figure is that the uniform phase change with time defines the slope of the trace sufficiently well so that the small frequency difference of 0.005 cps can be determined to at least 0.001 cps. This figure is an upper limit since it includes uncertainties caused by possible fluctuations in the source itself and by background noise in the amplifier pass band. At 300 miles, the signal-to-noise ratio was poorer giving a fuzzier phasemeter trace from which frequency differences cannot be determined as well. However, the tuning fork filters detected the signal distinctly and from the differences in output between adjacent filters, we can list an upper limit on line broadening of 0.01 cps. This does not mean that there was a measureable increase in line width at the large ranges but simply that we could not place as small an upper limit on it at the greater distances.

The limits that we have listed on the extent of possible line broadening show the existence of a central signal component sharply defined in frequency but they do not preclude the possibility of signal energy appearing in sidebands about this central component, as would be the case if the signal were subject to some kind of modulation. The observations, then, can be taken to indicate that the signal in its transmission through the water does not suffer any random phase variations or other types of modulation sufficient to alter the sharpness of the central frequency. If some signal energy is diverted into sidebands, they are inappreciable in the immediate vicinity of the central frequency, that is, within a few hundredths of a cps of it.

CONCLUSION

In conclusion, it can be stated that in regard to measuring sound pressure as a function of range over a region in which the transmission characteristics are of interest, the use of a continuous wave source enables results to be obtained directly without any lengthy analysis, as is required in evaluating shot data. A continuous source does not supplant shot work completely in that the latter enables individual arrival paths to be studied experimentally. In the direction north of our hydrophone installation at Puerto Rico,

shot data and a ray tracing analysis are available for comparison with the continuous source data. The agreement is fair insofar as it goes but the sparsity of continuous source measurements at the large ranges prevents a close comparison from being made in those regions. The incomplete coverage of the large ranges resulted from difficulties in towing the source.

In working with the continuous source, large dips in signal level, which were attributed to multi-path interference effects, were often noted. To avoid ambiguity, the practice was to read signal levels away from these fluctuations.

One of the principal objectives of these measurements was to determine a possible broadening of the signal in its passage through the ocean. The conclusions, which are stated in more detail at the end of the preceding section, are as follows: A 30 cps sound signal, although at times subject to large amplitude variations, which made phase measurements ambiguous, at other times maintains its phase coherency out to 300 miles, which is as far as we went. The use of arrays and sharp filters in long range listening systems designed to detect harmonic sound sources consequently appears to be well justified.

Acknowledgements

I am indebted to Dr. G. E. Becker and Mr. L. P. Goldberg for the many hours they spent in the operation of the source. The cooperation of the officers and men of the USS ALLEGHENY is also gratefully acknowledged.

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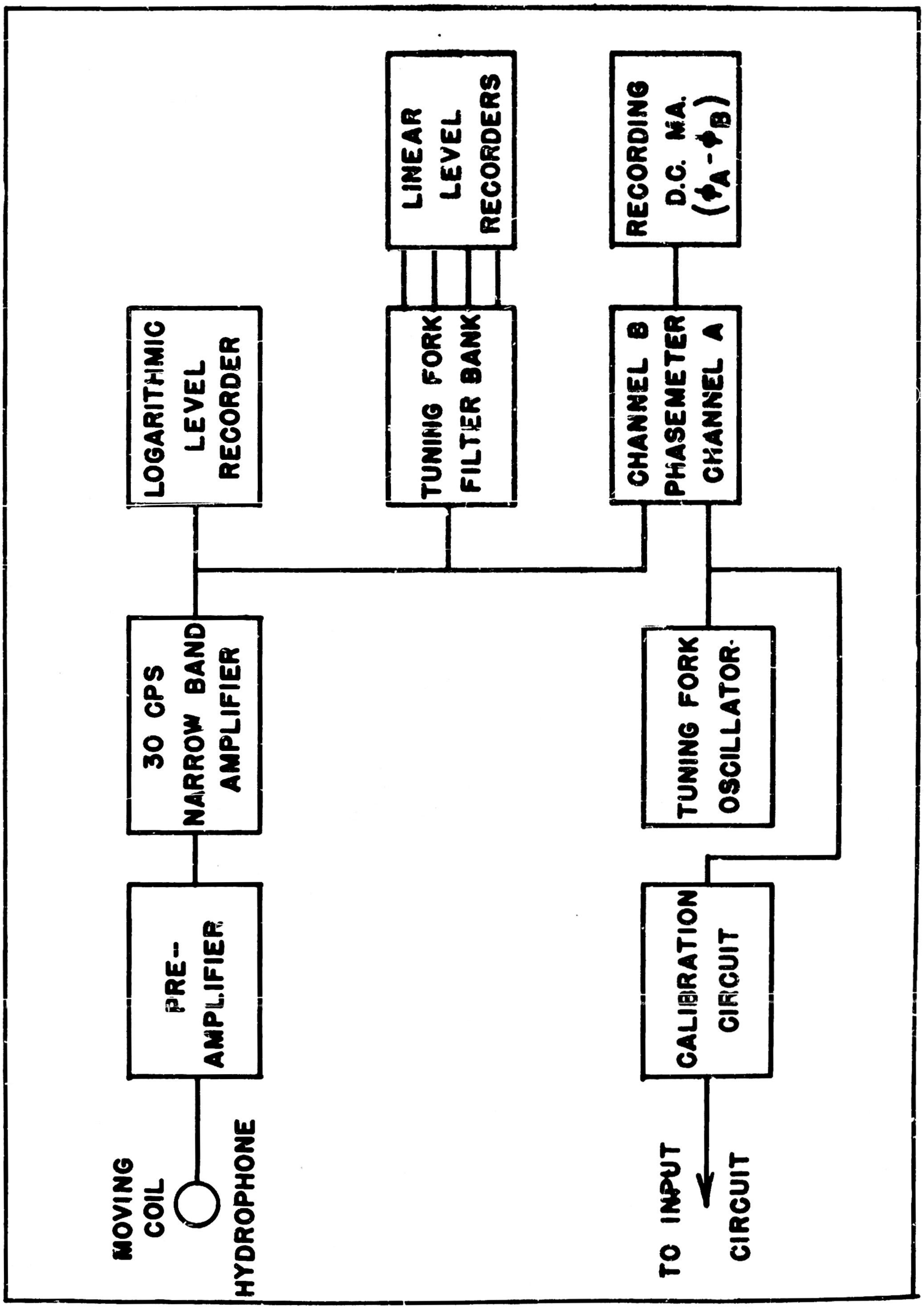
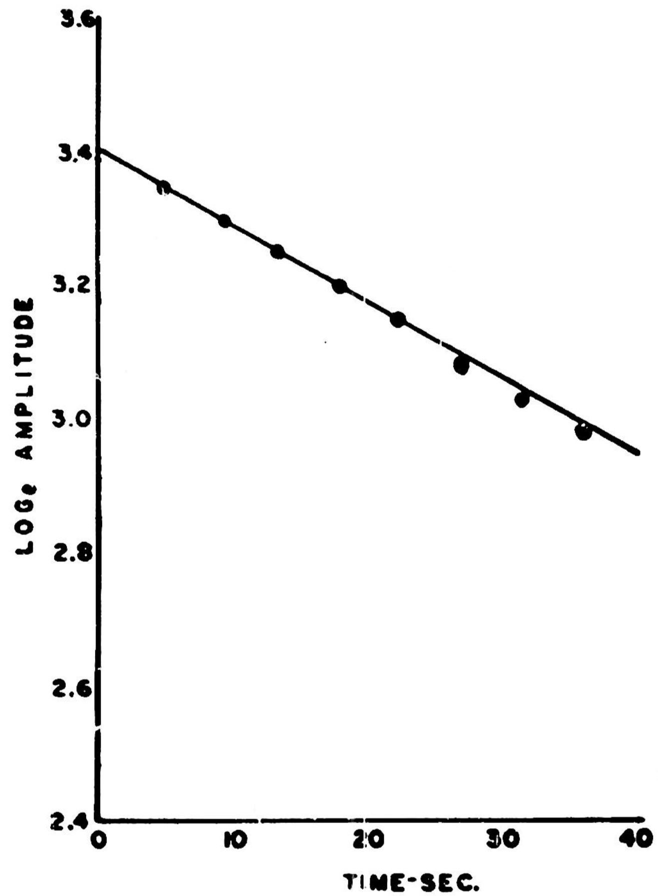


BLOCK DIAGRAM OF DETECTION EQUIPMENT

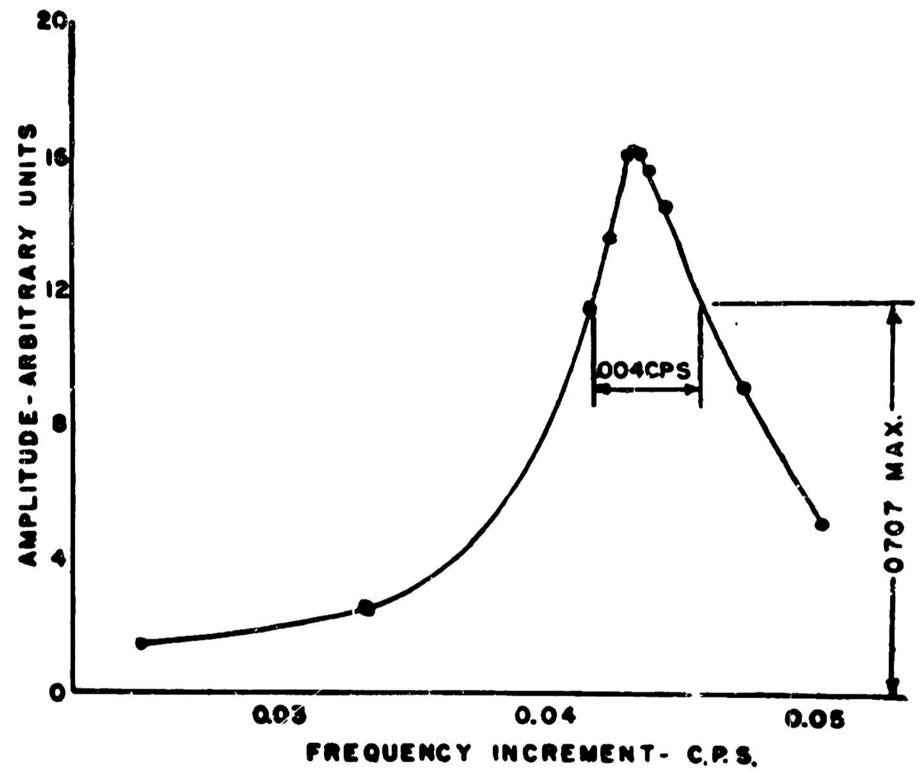
FIG. 1

DECAY OF 30 C.P.S. TUNING FORK FILTER
OSCILLATIONS (AMPLITUDE IN ARBITRARY UNITS)



TUNING FORK NO. ND482
Q=8300

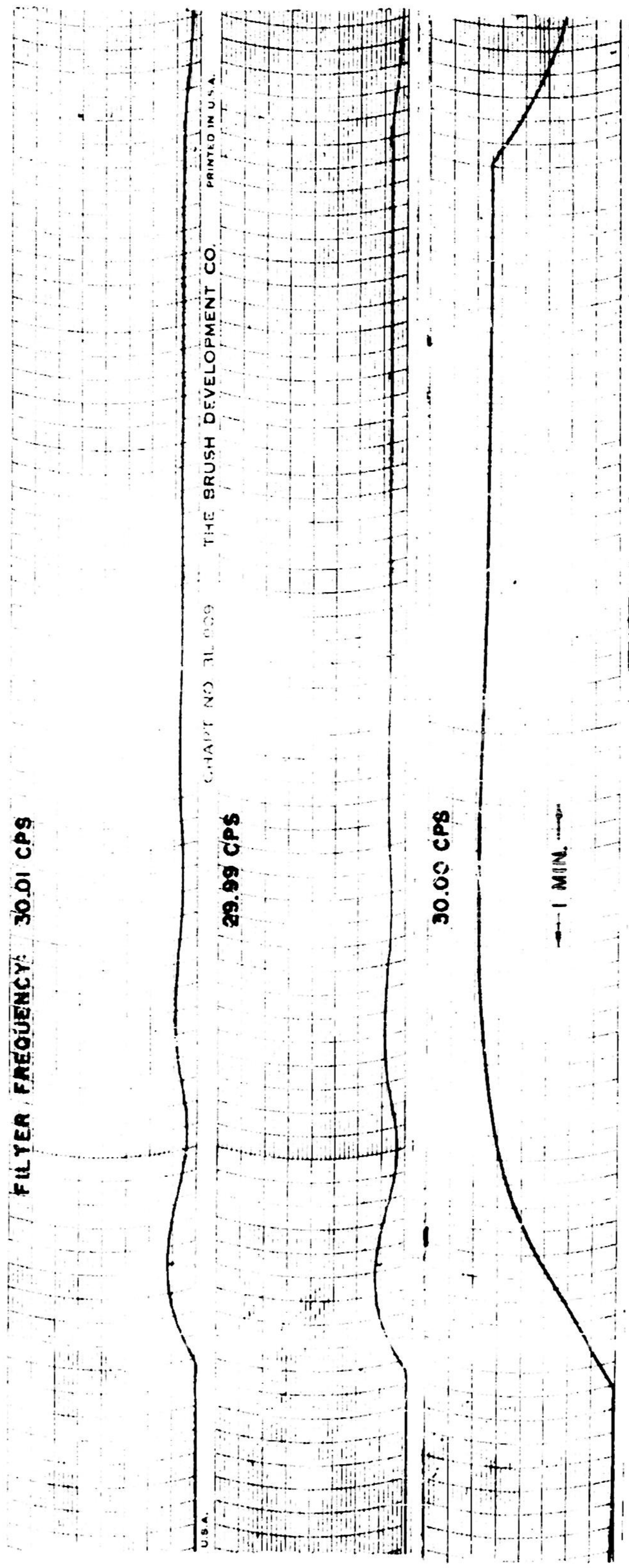
RESPONSE OF 30 C.P.S. TUNING FORK FILTER



TUNING FORK NO ND483
Q=7500

RESPONSE CURVES OF 30 C.P.S. TUNING FORK FILTER

a) DECAY OF OSCILLATIONS VERSUS TIME FIGURE 2 b) AMPLITUDE VERSUS FREQUENCY

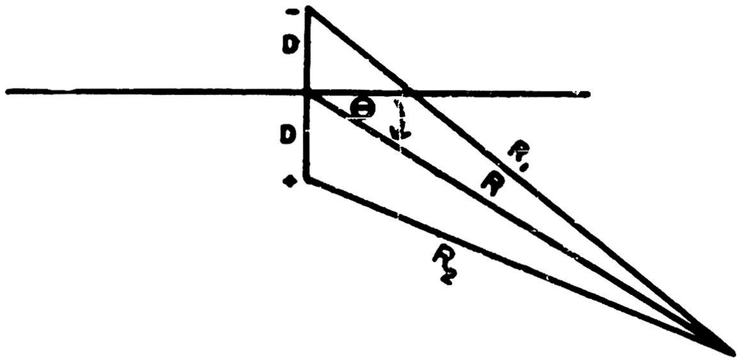


RESPONSE OF TUNING FORK FILTERS TO 30 CPS TEST SIGNAL

FIG. 3

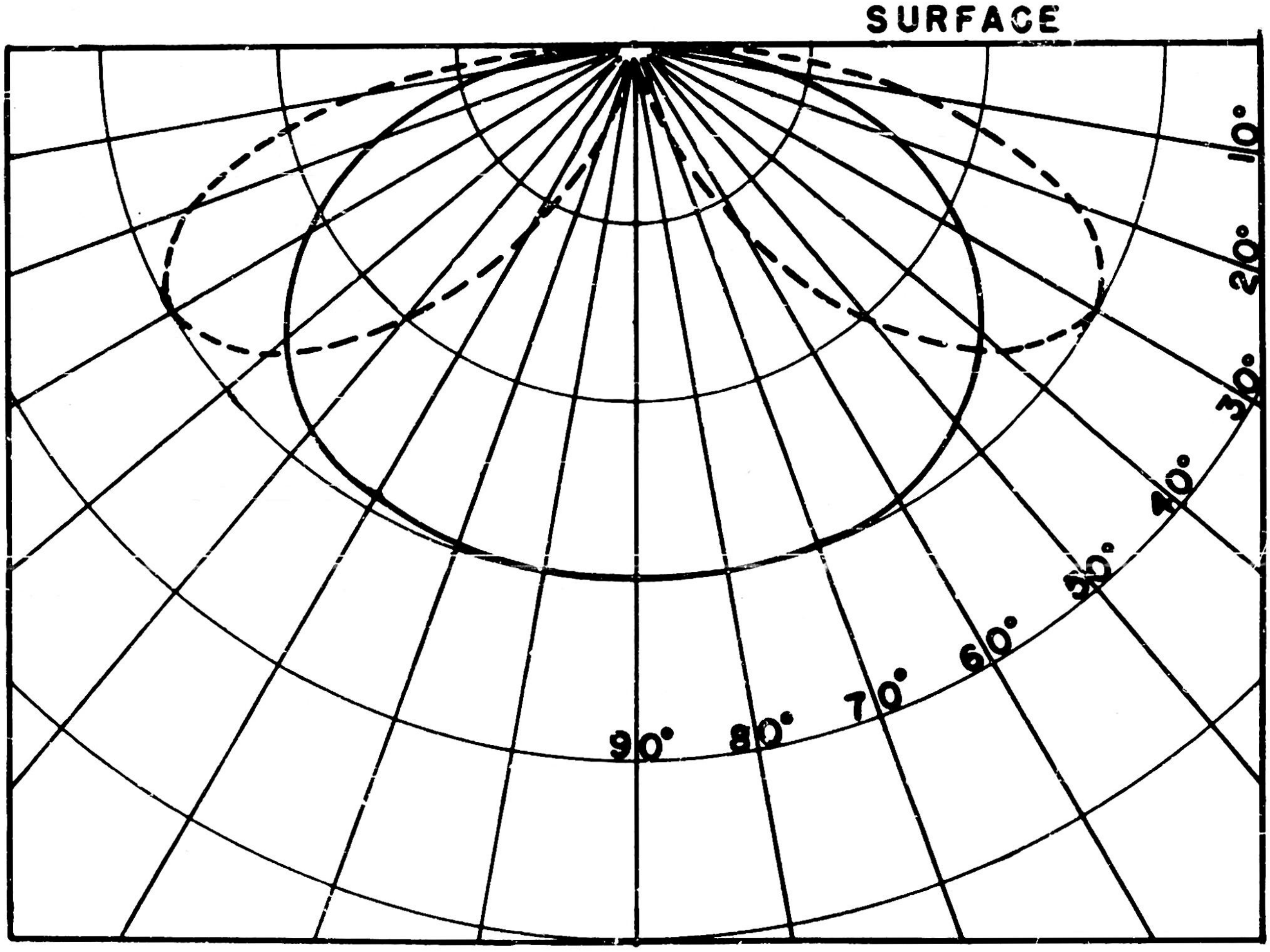
FIG. 4

RADIATION PATTERN OF SOURCE



—— SOURCE DEPTH: $\frac{\lambda}{4}$

- - - SOURCE DEPTH: $\frac{\lambda}{2}$



I HLP
12-53

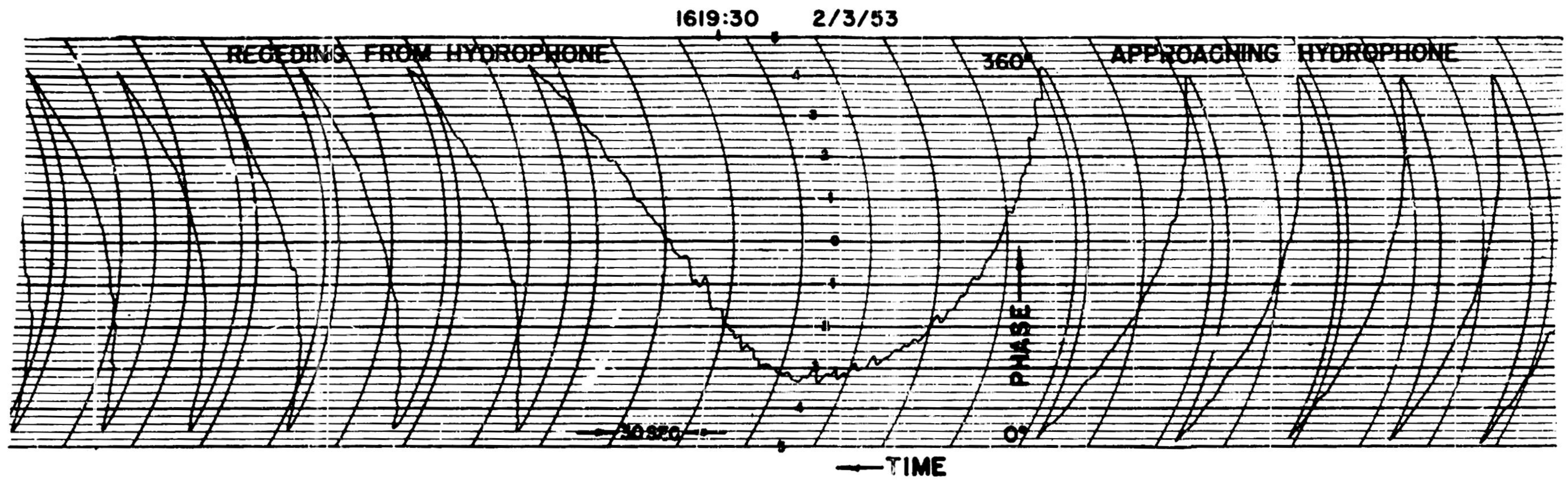


FIG. 5

SOUND SOURCE PASSING OVER SHALLOW HYDROPHONE (200 fa.), PUERTO RICO

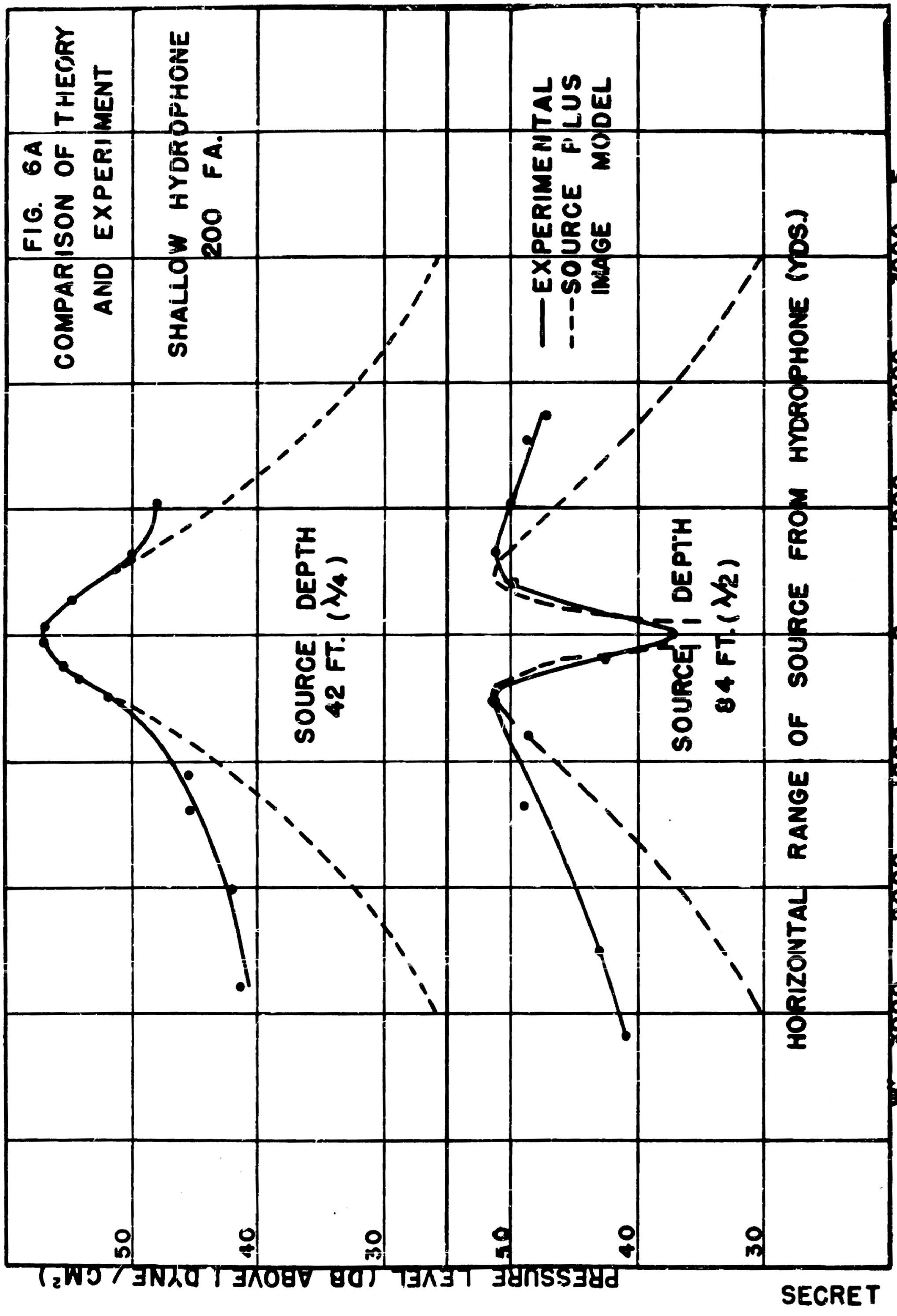


FIG. 6A
COMPARISON OF THEORY AND EXPERIMENT
SHALLOW HYDROPHONE 200 FA.
EXPERIMENTAL
SOURCE PLUS IMAGE MODEL
SOURCE DEPTH 42 FT. (λ/4)
SOURCE DEPTH 84 FT. (λ/2)
HORIZONTAL RANGE OF SOURCE FROM HYDROPHONE (YDS.)
E 3000 2000 1000 0 1000 2000 3000 W
PRESSURE LEVEL (DB ABOVE 1 DYNE / CM²)
50 40 30 50 40 30

2 HLP
12-53

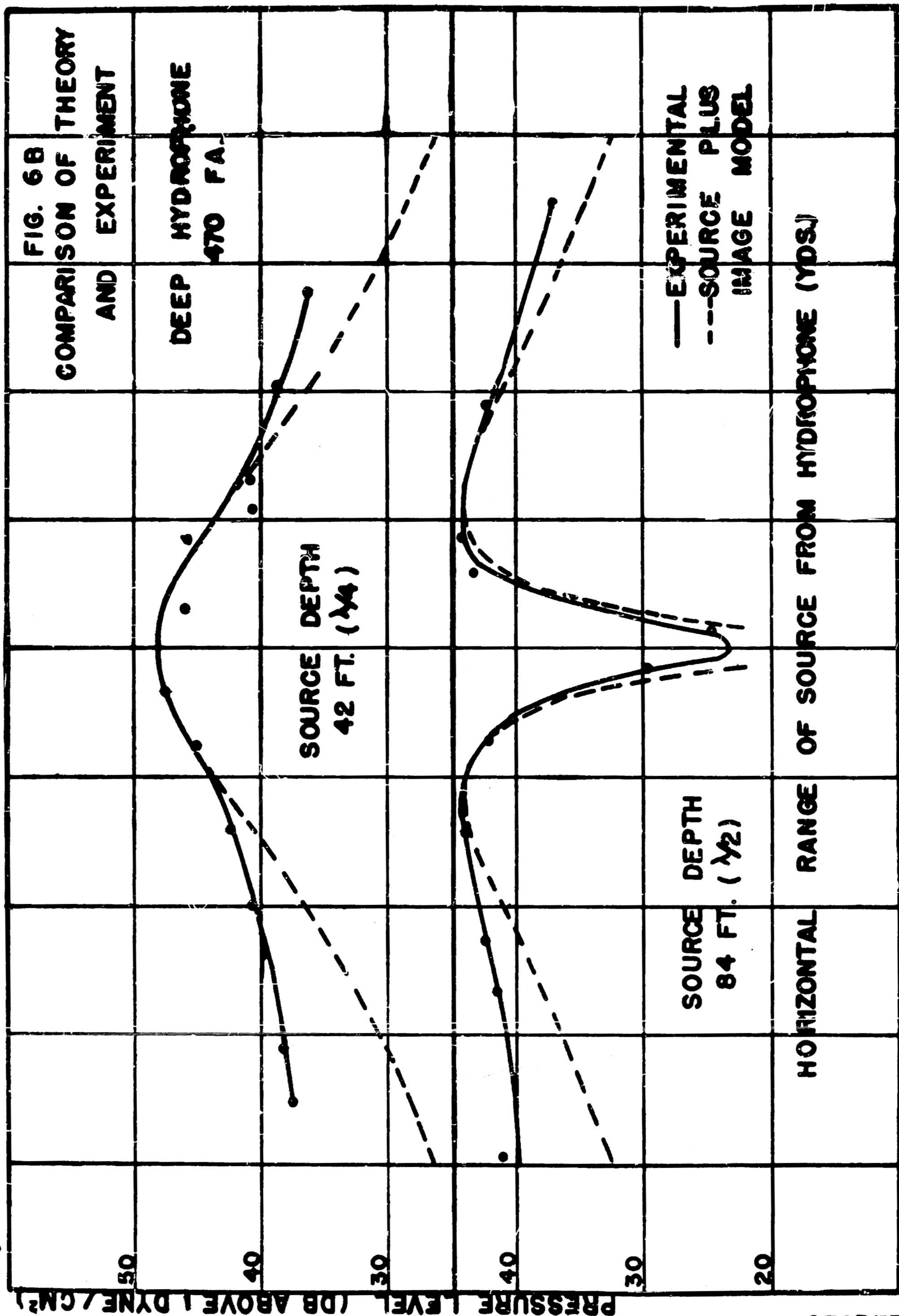


FIG. 6B
COMPARISON OF THEORY
AND EXPERIMENT
DEEP HYDROPHONE
470 FA.
SOURCE DEPTH
42 FT. (λ/4)
SOURCE DEPTH
84 FT. (λ/2)
—EXPERIMENTAL
---SOURCE PLUS
IMAGE MODEL
HORIZONTAL RANGE OF SOURCE FROM HYDROPHONE (YDS.)
PRESSURE LEVEL (DB ABOVE 1 DYNE/CM²)
50
40
30
40
30
20
W
4000
3000
2000
1000
0
1000
2000
3000
4000
E

3 HLP
12-53

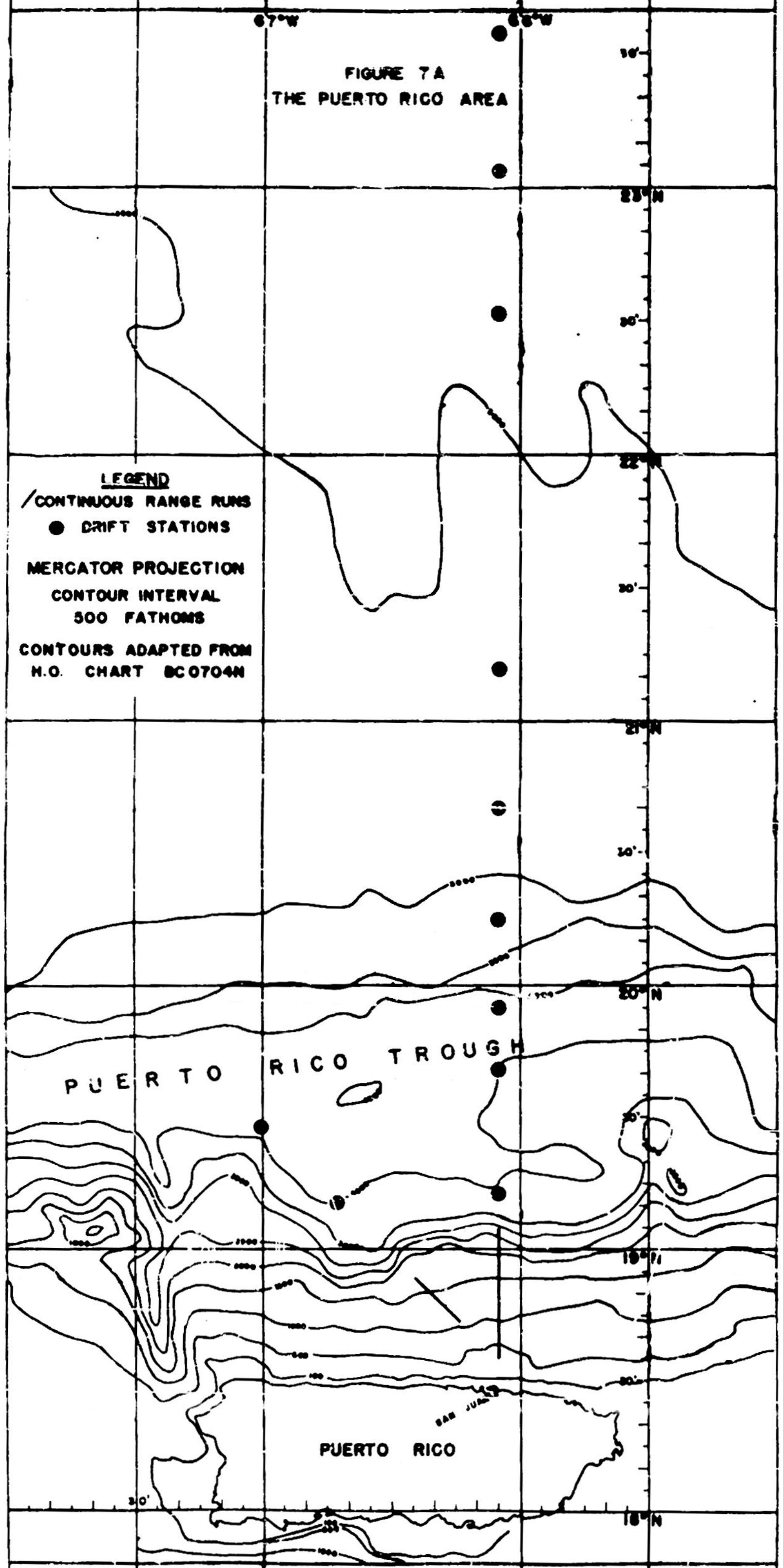


FIGURE 7A
THE PUERTO RICO AREA

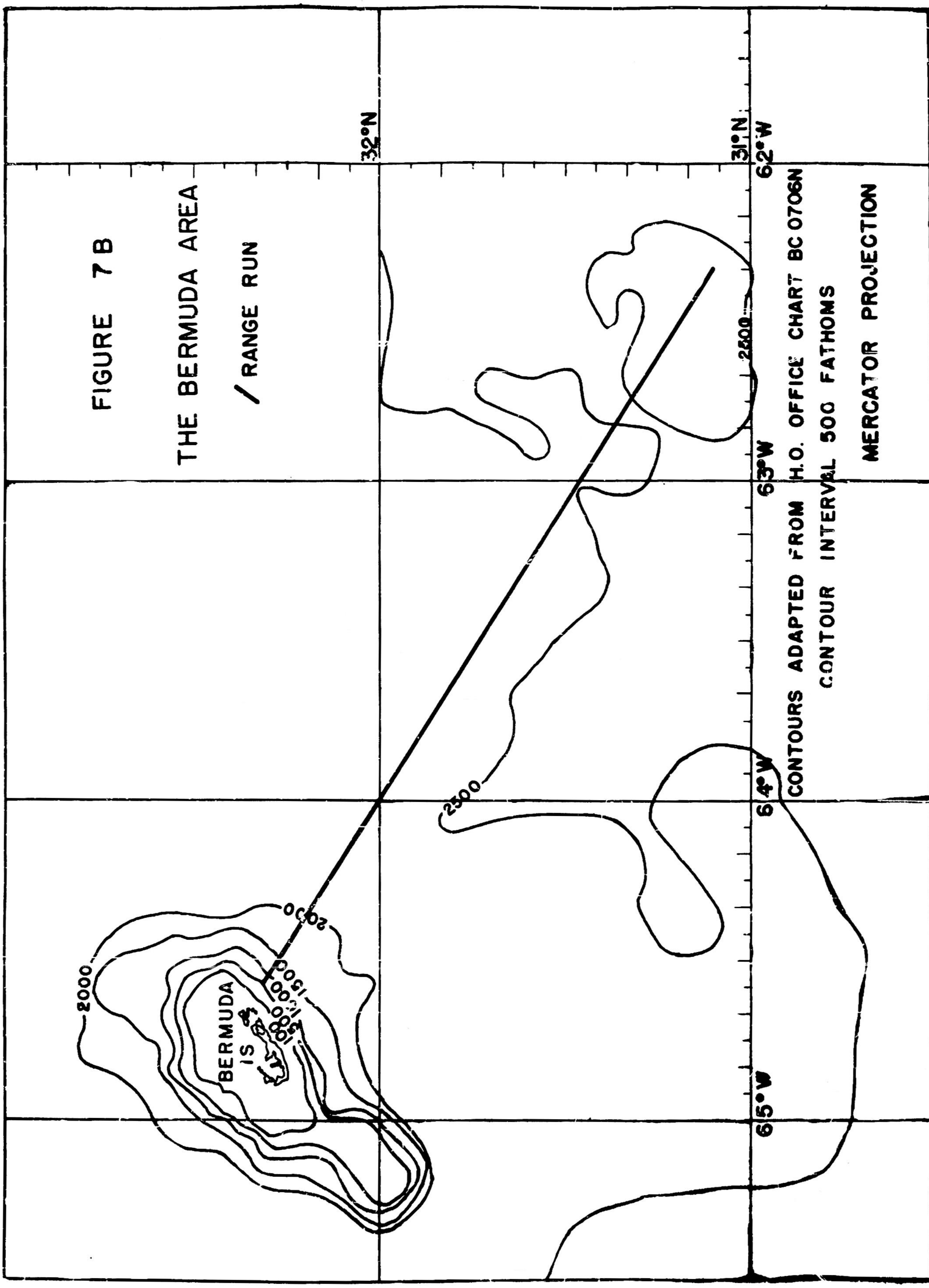
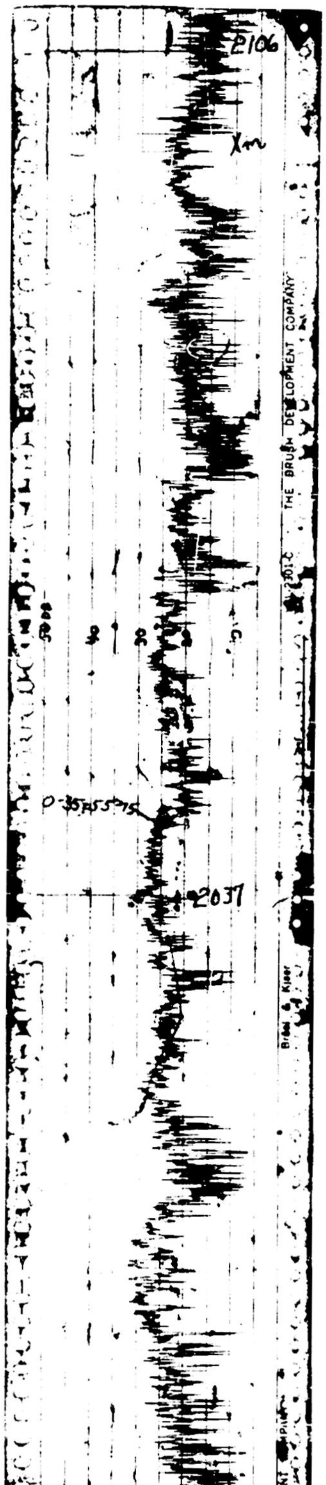


FIGURE 7 B
THE BERMUDA AREA
/ RANGE RUN
CONTOURS ADAPTED FROM H.O. OFFICE CHART BC 0706N
CONTOUR INTERVAL 500 FATHOMS
MERCATOR PROJECTION
32°N
31°N
62°W
63°W
64°W
65°W
2500
2300
2000
2000
1500
1000
500
BERMUDA IS



SOUND LEVEL AS RECEIVED BY THE BERMUDA SOFAR STATION GEOPHONE.
SOURCE DISTANCE: 120 MILES S.E.

FIG. 8

SECRET

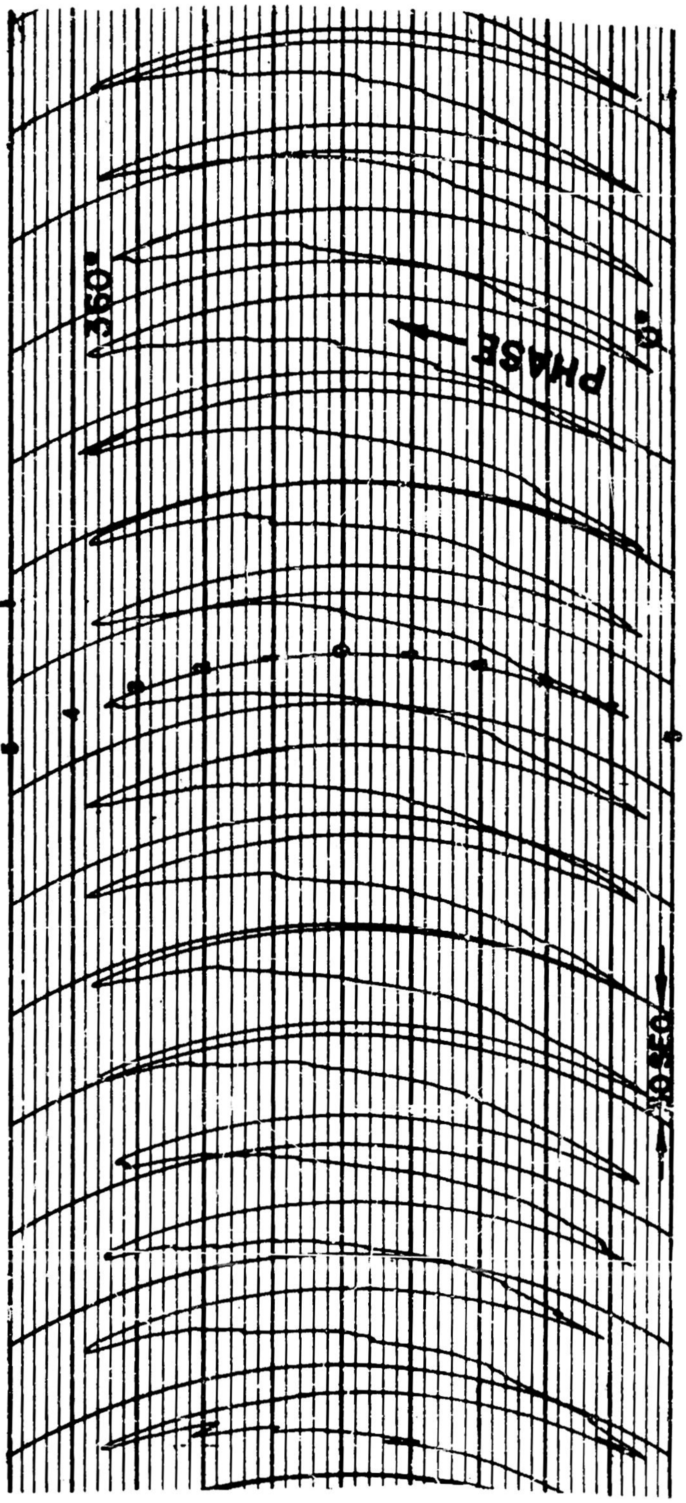
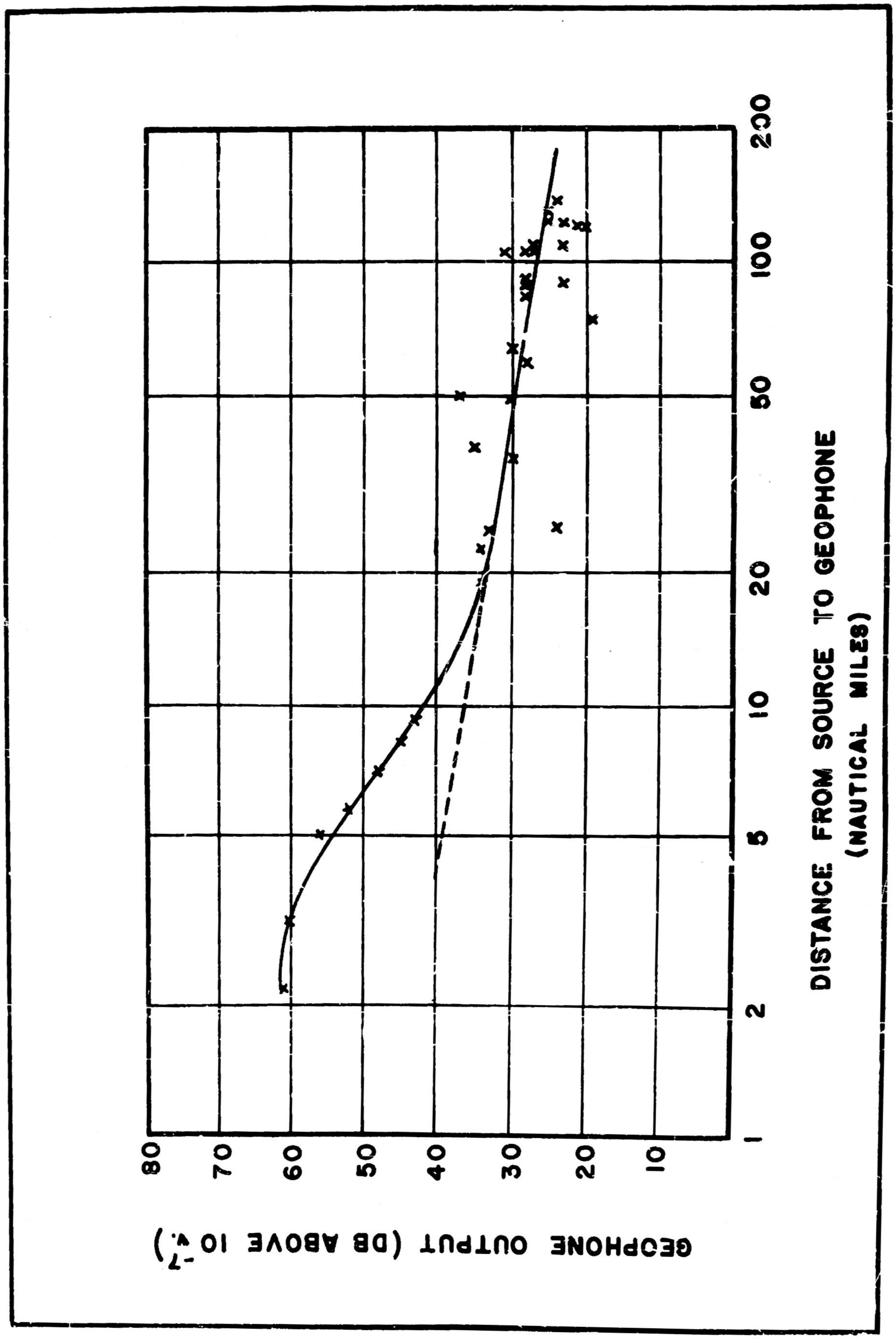


FIG. 9

SOUND SOURCE OPERATING 120 MILES S.E. OF BERMUDA SOFAR STATION GEOPHONE (425 fa.)

SECRET



BERMUDA RANGE RUN

FIG. 10

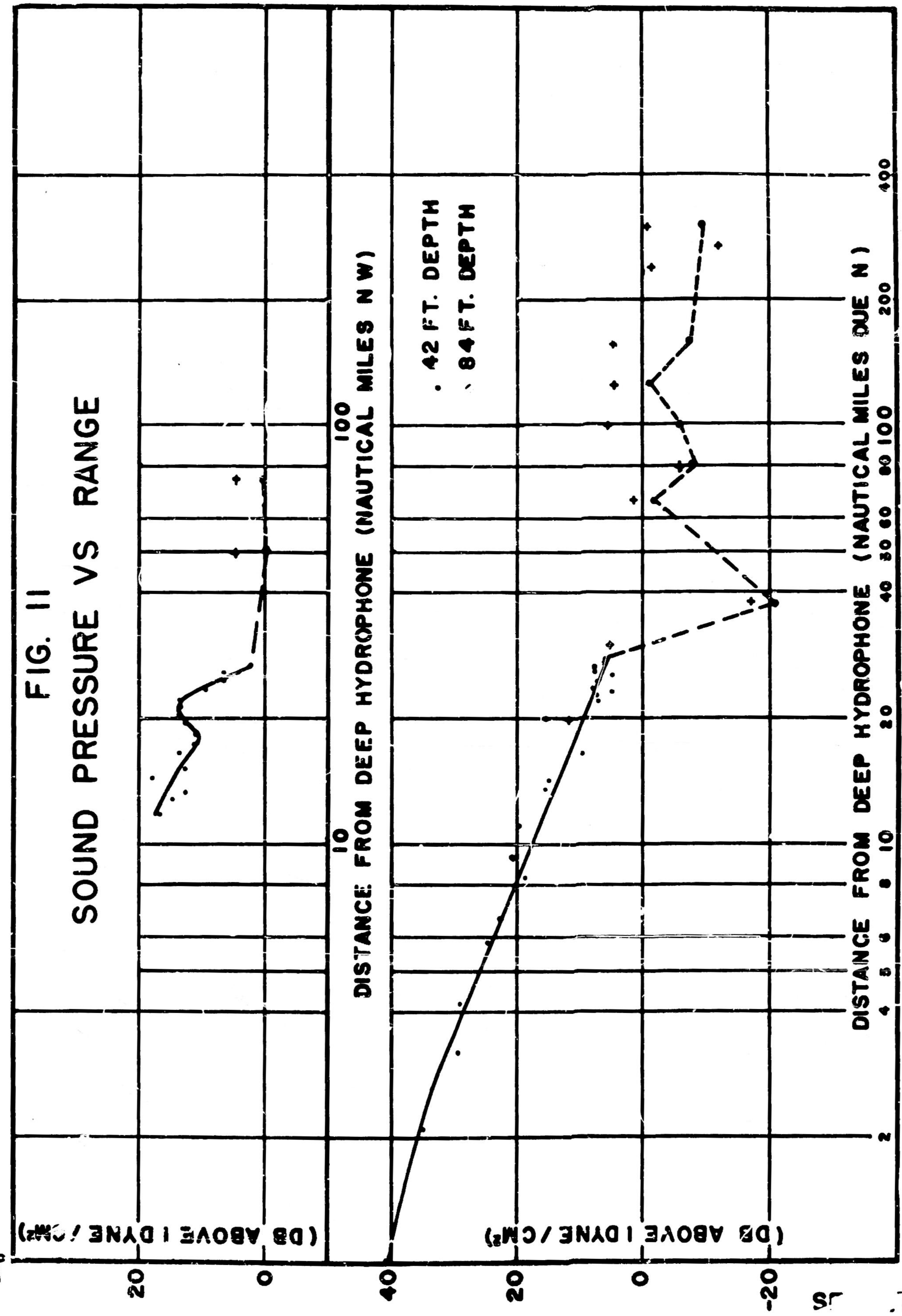
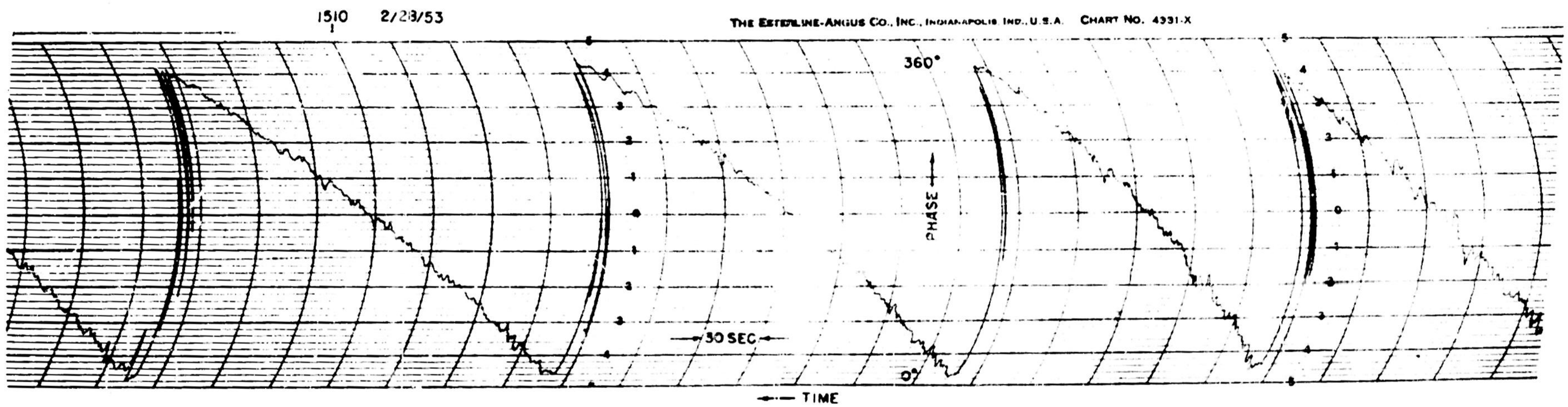


FIG. 11
SOUND PRESSURE VS RANGE



[illegible]ND SOURCE OPERATING 50 MILES N.W. OF DEEP HYDROPHONE (470 FATHOMS), PUERTO RICO

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